

Heterogeneity in Costs and Second-Best Policies for Environmental Protection

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Abstract

This paper investigates heterogeneity in pollution abatement costs using a computable general equilibrium framework. Previous literature using aggregated data has found that "grandfathered" tradable permits are dominated by other instruments including emission taxes, performance standards, and technology mandates because of interactions with pre-existing taxes. However, when the underlying costs of abatement are heterogeneous, a disaggregate representation of costs yields qualitatively different findings. In a disaggregate model of NO_x abatement in the United States, the relative performance of tradable permits improves significantly and out-performs command and control approaches over a wide range of emission reductions.

Key Words: cost-effectiveness analysis, general equilibrium, environmental policy, instrument choice, second-best regulation

JEL Classification Numbers: D58, H21, L51

Contents

1. Introduction.....	1
2. Motivation	3
3. Model.....	6
Heterogeneous Polluting Sector	6
Production	6
Utility	8
Government Revenue.....	8
Equilibrium	9
Aggregated Polluting Sector.....	9
Alternative Specifications of Abatement Technology.....	10
4. Data	12
General Economy	12
Abatement Costs.....	13
5. Characterization of policies.....	14
Emission Tax	14
Emission Permits	14
Performance Standard	15
Technology mandate	15
Evaluation of Policies.....	15
6. Findings.....	16
7. Sensitivity Analysis	24
8. Conclusion	27
References	29
Appendix.....	31

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1. Introduction

Partial equilibrium analysis is the usual tool for looking at the efficiency of environmental policy because it allows for detailed industry and firm specific data. This focus, however, is limited to a setting of fixed factor prices and consumer demand. The increasing availability of computable general equilibrium models has allowed for a more comprehensive look at the allocation of resources in the economy. Importantly, it has also allowed for incorporation of so-called “second-best” analysis, which takes into account pre-existing distortions away from economic efficiency, in evaluations of environmental policies. The broader perspective has yielded new and startling findings about the efficacy of policy instruments that have up-ended mainstream findings from the partial equilibrium literature.

Although general equilibrium models are sophisticated in their internal consistency, they often appear naïve with respect to technological characteristics of the economy compared to the detail that is present in partial equilibrium models. An important question is whether this level of detail is important. Can the level of detail in a general equilibrium model strongly influence the policy recommendations that it provides?

This paper investigates the value of disaggregate information about abatement cost in a general equilibrium evaluation of environmental policy instruments. We create a computable general equilibrium model and apply parameter values in the model representing the cost of reductions in nitrogen oxides (NO_x) emissions in the United States. Then we explore alternative formulations of the model to aggregate underlying heterogeneity in abatement cost data, and we compare these versions with respect to recent findings of the burgeoning literature on environmental policy in a second-best context.

Several recent papers have compared the social costs of alternative instruments such as command and control regulation, emission permits, and emission taxes. Under standard assumptions (Parry 1999), the literature offers two central findings. One is that the cost of a new regulation typically is estimated to be greater in a model that includes pre-existing distortions than in a model that

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ignores these distortions.² Our exploration indicates this finding is robust in the characterization of heterogeneity when other standard assumptions are held constant. The magnitude of the difference between estimates of regulatory costs in a partial equilibrium framework and those in a general equilibrium framework is affected, but the qualitative direction of the difference is unaffected.

The second central finding is that the relative cost-effectiveness of various policy instruments for environmental regulation can change substantially when pre-existing distortions are taken into account. General equilibrium studies that do not explicitly model cost heterogeneity (Goulder et al. 1999; Fullerton and Metcalf 1997) identify command and control policies (technology standards and/or performance standards) as more cost-effective than grandfathered tradable permits that do not raise revenues, over-turning two decades of economic intuition developed in partial equilibrium models.³ We replicate previous findings when abatement costs for NO_x reductions are aggregated, as in Goulder et al. (1999).

However, we find this result is sensitive to the characterization of heterogeneity. Importantly, the ordering of instruments in terms of cost-effectiveness is affected when heterogeneity is taken into account, yielding quite different policy recommendations. Grandfathered permits out-perform command and control policies over nearly the entire range of reductions.

Two aspects of a system of tradable permits are relevant to our findings. One is the “heterogeneity advantage” relative to command and control policies by moving closer to equality in marginal abatement costs. The other is the “tax-interaction disadvantage,” due to the fact that a system of tradable permits has a more costly interaction with pre-existing taxes than do command and control policies.⁴ We find that in an empirical application of NO_x reductions in the United States, the former dominates in all except the very first portion (less than 4%) of emission reductions. This finding is of general relevance in guiding economic modeling for environmental policy; and it is of specific relevance to current regulatory efforts of the U.S. Environmental Protection Agency (EPA) and various state governments aimed at achieving reductions in NO_x.

This paper is organized as follows: The next section provides further motivation for the analysis by illustrating the potential for bias in the aggregation of data. Section 3 describes our model, Section 4 describes the data, and Section 5 lists the characterization of policies. Section 6 presents our findings, Section 7 offers sensitivity analysis, and Section 8 concludes.

² Williams (1998) investigates an analogous proposition, in which benefits of environmental policies may be underestimated in a model that excludes pre-existing distortions.

³ Goulder et al. (1999) offer the explicit caveat that heterogeneity may be an important issue that was excluded from their investigation. They investigate the relative cost of policies over 100% of the range of possible emission reductions, while Fullerton and Metcalf (1997) only consider relative costs for the first unit of abatement.

⁴ We are grateful to Larry Goulder for suggesting this characterization of the problem.

2. Motivation

Economic modeling depends on parsimony in characterizing the economy and technology. The motivation for this paper is to identify the degree to which aggregation of cost data has an effect on the policy prescriptions in economic models.

The previous general equilibrium literature on environmental policy has either abstracted away from heterogeneity in abatement costs or has not modeled abatement cost explicitly.⁵ Most often, the context for investigating environmental policy in a second-best setting has been the analysis of policies to reduce carbon dioxide emissions.⁶ For this problem, abatement technologies are of little relevance, and most emission reductions are achieved through input substitution. However, we know of no study that has examined heterogeneity in relation to the opportunity for input substitution in this context.⁷

Abatement costs are considered explicitly in a general equilibrium model in the context of the sulfur dioxide trading program by Goulder et al. (1997), who compared the performance of (grandfathered) tradable permits with a revenue-raising tax. Goulder et al. (1999) and Fullerton and Metcalf (1997) considered a broader set of policy instruments including command and control regulation. These studies employed only aggregate abatement cost functions for the polluting sector, yielding different results than those in this paper. One can easily illustrate how heterogeneity in abatement costs may matter in evaluating the cost of alternative policies. Consider a sector with two constituent industries, one with low and one with high marginal abatement cost curves. One way to construct a sector-level aggregate of abatement costs would be to calculate a vertical sum of the total abatement costs at each level of emission reduction for the constituent industries. The change in aggregate total abatement costs at each increment of emission reduction would map out an aggregate marginal abatement cost schedule. When the percent reduction in emissions is constrained to be equal among the constituent industries, the aggregate marginal abatement cost schedule is equivalent to the emission-weighted vertical mean of the marginal abatement cost schedules for the constituent industries.⁸ This is illustrated with the heavy solid line in Figure 1.

⁵ For example, see Bovenberg and de Mooij (1994) and Bovenberg and Goulder (1996).

⁶ For example, see Carraro and Gallo (1996), various authors in Carraro and Siniscalco (1996), and Parry, Williams, and Goulder (1998). A recent review is contained in de Mooij (1999).

⁷ Bye and Nyborg (1999) compare carbon taxes that are differentiated (in order to reduce political resistance) with tradable grandfathered permits, and find that differentiated taxes yield higher welfare.

⁸ The weights account for different quantities of baseline emissions (before abatement).

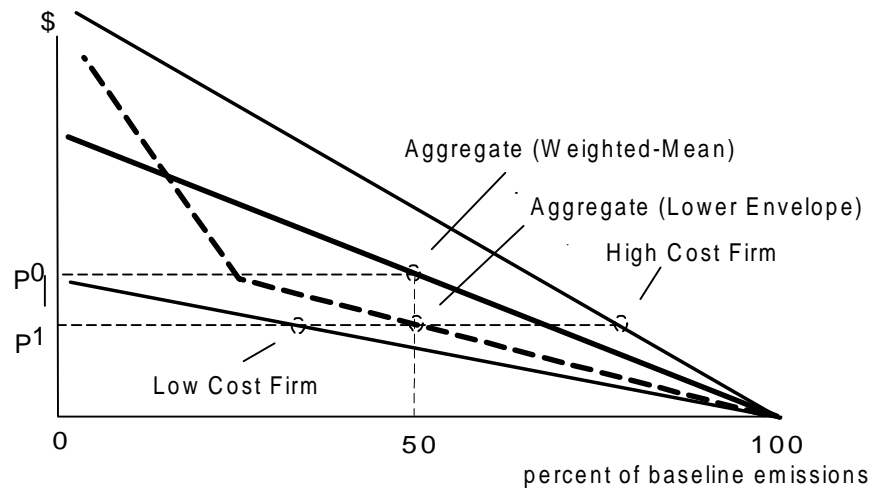


Figure 1: Two ways to aggregate marginal abatement cost.

By construction, the aggregate (weighted-mean) marginal abatement cost schedule in Figure 1 is accurate for the evaluation of a uniform percent reduction in emissions, as may describe a performance standard. However, if an alternative such as tradable emission permits is contemplated, the schedule will not provide an accurate indication of costs, because tradable permits allow firms to reduce total costs by equating marginal costs of emission reduction. In Figure 1, a 50% emission reduction can be achieved at a marginal cost of P^0 under a performance standard, but a marginal cost of P^1 would result under permit trading, since the constituent industries could exchange obligations to reduce emissions. If marginal abatement costs are linear (as in Figure 1), the more heterogeneous are the marginal costs of the constituent firms, the lower will be the marginal costs of a trading program at every level of emission reduction (Ben-David et al. 1999). However, greater heterogeneity will not affect the predicted marginal cost under a performance standard. Hence, a systematic bias may emerge when comparing instruments using mean marginal abatement costs as an aggregate representation of constituent marginal costs. Further, if the industry aggregates are themselves mean representations of marginal abatement costs for their constituent firms, and if firms are aggregates of plants and plants are aggregates of generating units, then the actual cost of a trading program could be even greater than a prediction that relies on an aggregate representation of the sector.

A focus of this paper is whether the sensitivity to aggregation in the comparison of instruments in a partial equilibrium framework is equally important when comparing instruments in a general equilibrium framework. One reason it may be important is that with constant returns to scale production and perfect competition, a performance standard will impose a change in the cost of a product that is largely due to the change in abatement cost. However, for tradable permits, there is an additional opportunity cost equal to the value of the emission permits used for compliance. Since permit price presumably equals the marginal cost of abatement, if the marginal cost is

overestimated, then both the compliance cost and the permit cost are biased high, compounding the bias in the predicted change in product price.⁹

The bias may be compounded further when comparing instruments in a model that accounts for pre-existing distortions away from economic efficiency in factor markets, such as a tax on labor income. The interaction of an environmental regulation with a pre-existing labor tax stems from the effect of the regulation on product price, the effect this has on the real wage of workers, and in turn, on the labor-leisure trade-off and the supply of labor (Parry 1995).

In summary, it is possible that if the representation of marginal abatement cost for tradable permits is too high, the error will be magnified in the predicted change in product prices, it will affect labor supply, and it will affect the calculation of social welfare in evaluating alternative policies. Goulder et al. (1999) find that pre-existing taxes raise the social costs of an emissions tax, a performance standard, and a technology mandate by a factor of about 27% over the cost of these policies in a model absent pre-existing taxes.¹⁰ This percentage applies for the entire range of emission reductions. However, pre-existing taxes are found to raise the cost of tradable permits by significantly more. Hence, an overestimate of marginal abatement costs may severely penalize tradable permits relative to other instruments when viewed in a general equilibrium context.

The remedy to this problem might be to use a different approach in constructing an aggregation of abatement costs. Imagine that instead of using the (emission-weighted) mean of constituent marginal abatement costs, one was to assume cost-effectiveness in pollution abatement involving disproportional emission reductions by the affected industries. This could be illustrated as the *lower envelope* of marginal costs among constituent industries in the sector, represented by the broken line in Figure 1. This aggregate accounts for the flexibility implicit in a permit or tax approach by reflecting the most cost-effective way of achieving those reductions. However, evaluating either a performance standard that requires equal percentage reductions at each constituent firm, or a technology standard that requires specific investments at various plants, would also yield unexpected results. This time the aggregate marginal abatement cost schedule would be in error by under-estimating costs that would result from policies that were implemented in a uniform and inflexible way. This error would be passed through the model in the calculation of product prices and social welfare, again imposing a bias in the comparison of instruments.

A uniform approach to constructing aggregate marginal cost schedules is inherently problematic when using these schedules to compare alternative policy instruments. However, general equilibrium models inherently depend on an aggregate representation of detail in the economy. The questions before us are: whether there is a potential bias contained in the use of aggregate cost data, and is it significant enough to affect the conclusions of economic analysis.

⁹ This is offset to some degree by the role of input and output substitution, which provides alternative channels for emission reduction and lowers the cost of tradable permits relative to command and control instruments in a general equilibrium setting. We examine these channels in sensitivity analysis.

¹⁰ Goulder et al. (1997) find the factor to be about 30% for an emissions tax.

3. Model

We employ a numerical static general equilibrium model using constant returns to scale, constant elasticity of substitution (CES) forms in the production and utility functions. The model has two basic formulations. The disaggregated formulation contains a heterogeneous characterization of the abatement cost in polluting intermediate industries. The second formulation represents these industries at a higher level of aggregation.

Heterogeneous Polluting Sector

The production relationships in the disaggregate case with heterogeneous characterization of the abatement cost among a set of polluting industries are illustrated in Figure 2. The notation is summarized in Table A1 in the appendix. Each diagram in the figure represents a production activity linking inputs (indicated at the bottom of each diagram) with utility or output (indicated at the top). Nodes linking inputs represent opportunities for substitution in production.

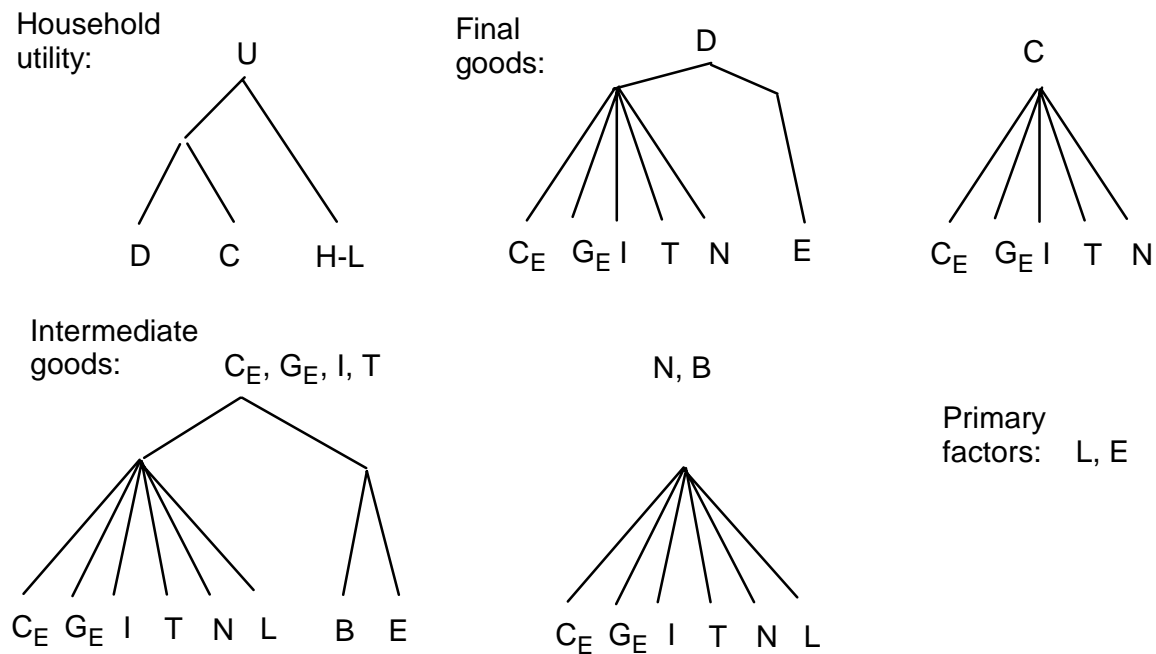


Figure 2: Nesting structure for the heterogeneous model.

Production

Two final consumption goods are distinguished by the intensity of emissions. Direct emissions result from the dirty consumption good (D). We assume that there are no opportunities to abate these emissions and that they are unregulated. Production of the relatively clean consumption good (C) does not directly result in emissions.

The productive sub-nest for final consumption goods is represented through CES production functions having the form:

$$F_p = \left[\sum_{M=C_E, G_E, I, T, N} \theta_{F_p, M} M^{\rho_{F_p}} \right]^{\frac{1}{\rho_{F_p}}}; \text{ where } \sum_{M=C_E, G_E, I, T, N} \theta_{F_p, M} = 1; F_p = \{D_p, C_p\}$$

For the dirty consumption good, emissions substitute in a Leontief relationship with production. The upper level nest of final good production has the CES form:

$$F = \min \left[F_p, \frac{\theta_F}{(1-\theta_F)} E_F \right]; \theta_F = 1 \text{ for } F = C; F = \{D, C\}$$

The production of intermediate goods also is composed of a productive sub-nest and emissions. Unlike final goods, intermediate goods have labor as an input to production. The productive sub-nest has the CES form:

$$M_p = \left[\sum_{M=C_E, G_E, I, T, N, L} \theta_{M_p, M} M^{\rho_{M_p}} \right]^{\frac{1}{\rho_{M_p}}}; \text{ where } \sum_{M=C_E, G_E, I, T, N, L} \theta_{M_p, M} = 1; M_p = \{C_E, G_E, I, T, N, B\}$$

The emission-intensive intermediate goods include coal-fired electricity (C_E), gas-fired electricity (G_E), industrial combustion (I) and transportation (T), and have an emissions sub-nest that combines with the productive sub-nest in a CES function. We employ identical parameter values and constant returns to scale for the productive sub-nest for the polluting intermediate goods, implying that the polluting intermediate industries are scaled versions of each other with respect to production. The emission-non-intensive intermediate good (N) and abatement (B) have no emissions. The upper level nest of intermediate good production has the form:

$$M = \left[\theta_M M_p^{\rho_{Mu}} + (1-\theta_M) B E_M^{\rho_{Mu}} \right]^{\frac{1}{\rho_{Mu}}}; \theta_M = 1 \text{ for } M = N, B; M = \{C_E, G_E, I, T, N, B\}$$

The aggregate of abatement (B) and actual emissions (E) can be thought of as “potential emissions” in the production of intermediate goods. An innovation of this formulation is to characterize B and E as substitutes and to acknowledge that positive levels of abatement are observed in the baseline in the model.¹¹ This reflects the fact that there are various types of controls in place for NO_x even before implementation of the 1990 Clean Air Act Amendments, so the marginal cost for the first increment of reduction is greater than zero.¹² When the allowable

¹¹ This allows for positive value shares for both B and E in the calibration of the CES production functions.

¹² In sensitivity analysis we find that variation in the absolute level and/or the relative level of abatement in the benchmark has an affect on the relative performance of policy instruments. McKittrick (1999)

amount of emissions is reduced, the BE aggregate exhibits increasing convex costs in the substitution of abatement for emissions. The production of the BE aggregate has the form:

$$BE_M = \left[\theta_{b,M} B_M^{\rho_{Mb}} + (1 - \theta_{b,M}) E_M^{\rho_{Mb}} \right]^{\frac{1}{\rho_{Mb}}}; \quad M = \{C_E, G_E, I, T\}$$

Finally, the primary factors of production are labor (L) and emissions (E). Total emissions from the intermediate production sectors are constrained to equal the allowable regulated emissions under the various policy instruments ($\sum_{M=C_E, G_E, I, T} E_M = E_R$).

Utility

Household utility depends on leisure and consumption. The bundle of consumption goods is weakly separable from leisure, and includes the dirty consumption good (D) and the clean consumption good (C). The representative household receives an endowment of time (H) that it allocates to labor (L) or leisure ($H-L$), with income from labor (less government taxes), transfers from government, and economic rents (manifest under the tradable permit policy) available to pay for consumption.

Household utility is represented through a nested CES utility function:

$$U = \left[\theta_U (H-L)^{\rho_U} + (1-\theta_U) \left(\theta_{Ug} D^{\rho_{Ug}} + (1-\theta_{Ug}) C^{\rho_{Ug}} \right)^{\frac{\rho_U}{\rho_{Ug}}} \right]^{\frac{1}{\rho_U}}$$

The household maximizes utility subject to the household budget constraint. When emissions are controlled through an emissions tax, technology mandate, or performance standard, the household budget constraint is represented by:

$$p_L (H-L) + \sum_{X=D,C} p_X X = p_L H + TR$$

When emissions are controlled through tradable permits, households also receive rents from the ownership of these permits. A portion of the rents is taxed away by the government, at a tax rate of τ_E . The household does not receive rents from emissions that are unregulated (E_F). In the tradable emission permit scenario, the household budget constraint is:

$$p_L (H-L) + \sum_{X=G,O,C} p_X X = p_L H + TR + (1-\tau_E) p_E E_R$$

Government Revenue

The tax on labor is set endogenously such that government revenue is held constant at a benchmark level. Under the technology mandate and performance standard the tax on labor is the sole source of government revenue.

demonstrates how the cost-effectiveness of policy instruments at the firm level can be affected by non-differentiability of the abatement cost function as well as the level of abatement.

$$TR = \tau_L p_L L$$

Under a tradable permit policy, the government collects revenues through the tax on permit rents collected by households.

$$TR = \tau_L p_L L + \tau_E p_E E_R$$

Under the emissions tax scenario, government revenue is raised both from the tax on labor and the tax on regulated emissions. Since the sum of revenue from the labor tax and emission tax equals benchmark government revenue, the labor tax is lower than in the absence of revenues from the emission tax.

$$TR = \tau_L p_L L + p_E E_R$$

Equilibrium

The model is solved using GAMS/MPSGE software (Rutherford 1995). A solution is comprised of a set of final goods, intermediate goods and primary factor prices, production sector activity levels, and household income levels such that the following set of inequalities are satisfied:

- Zero profit for each production sector: The user cost of inputs used in production is greater than or equal to the value of output.
- Market clearance for goods and primary factors: Production output and initial endowment is greater than or equal to intermediate and final demand.
- Income balance for households: Expenditure equals income from factor ownership and redistribution of tax revenue.

The series of inequalities are solved as a mixed complementarity problem: activity levels are complementary with zero profit conditions, prices are complementary with market clearance, and income is complementary with income balance. When endogenous taxes are included in the model, the endogenous tax is complementary with the equation determining the tax rate.

Aggregated Polluting Sector

The production relationships under an aggregate representation of abatement opportunities in the intermediate industries are illustrated in Figure 3. In this picture, the four polluting intermediate goods from the Heterogeneous Case (C_E , C_G , I , T) are aggregated to one sector (M). This picture illustrates both the Homogeneous Case and the Lower Envelope Case, which are distinguished only by the elasticity of substitution in the BE aggregate. The equations governing production and utility in the model are unchanged, with the exception that the index $M = \{C_E, C_G, I, T\}$ becomes a single aggregate (M).

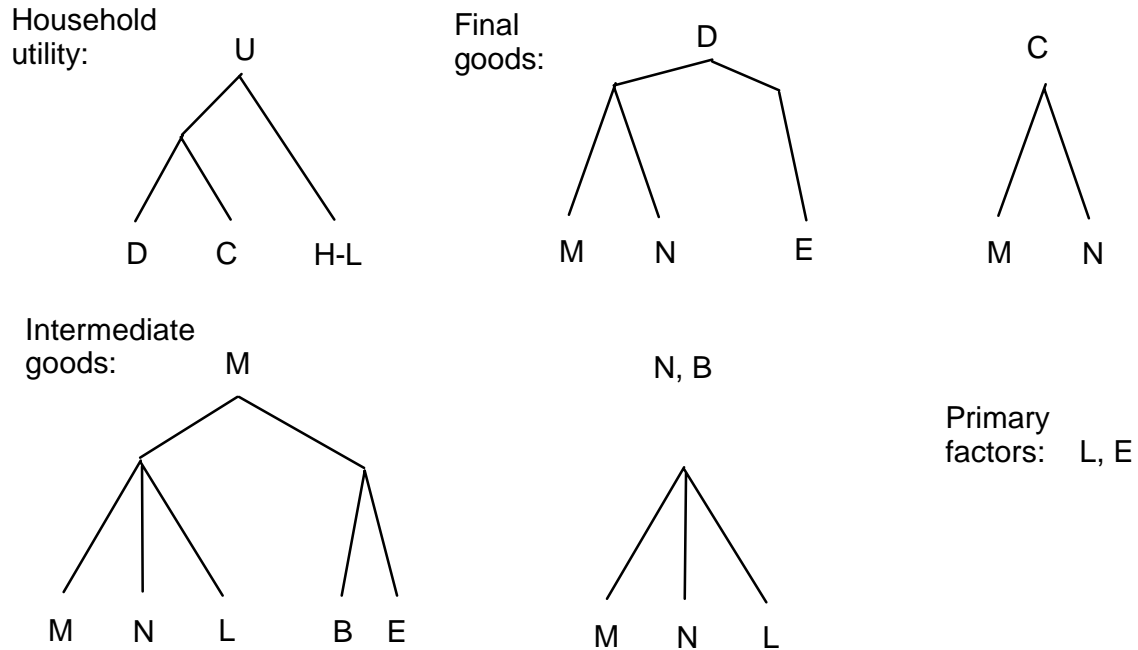


Figure 3: Aggregate nesting structure for the Homogeneous and Lower Envelope Cases.

Alternative Specifications of Abatement Technology

Differences in the BE sub-nest of the production functions distinguish the three alternative cases we examine. The partial equilibrium cost of abatement is represented in the general equilibrium CES production function by the elasticity of substitution between the emission and abatement inputs used in the production of the dirty industries, and the level of abatement and emissions in place in the benchmark. In the Heterogeneous Case, these parameters vary among the four polluting intermediate industries. When regulation reduces the allowable emissions, differences in the cost of abatement emerge causing a shift in production among the industries. All industries remain active despite differences in abatement costs because their outputs are not perfect substitutes.

We term one aggregate model the Homogeneous Case. In this case, abatement expenditures and emissions for the four constituent industries are summed and applied to the aggregated industry. The elasticity of substitution in the abatement cost function is derived so that the partial equilibrium cost of abatement is equal to the sum across constituent industries for equal increments of emission reduction.¹³ This approach would correspond to many sources of data that

¹³ The elasticities of substitution for the industries in the Heterogeneous Case are constant. The equalization of total costs is achieved by calculating a different elasticity of substitution at each level of emission reduction for the Homogeneous Case, and also for the Lower Envelope Case described subsequently.

report costs of complying with technology or performance standards that impose uniform requirements across an industry.

A second aggregate model is termed the Lower Envelope Case. This illustrates the cost-effective schedule for emission reductions, given the variability of the underlying data in the Heterogeneous Case. This approach would correspond to a “bottoms-up” identification of emission reductions, or the presumption that emission reductions would be achieved in a cost-effective manner. The partial equilibrium abatement cost functions for both aggregate models, and for the four constituent industries in the Heterogeneous Case are illustrated in Figure 4.

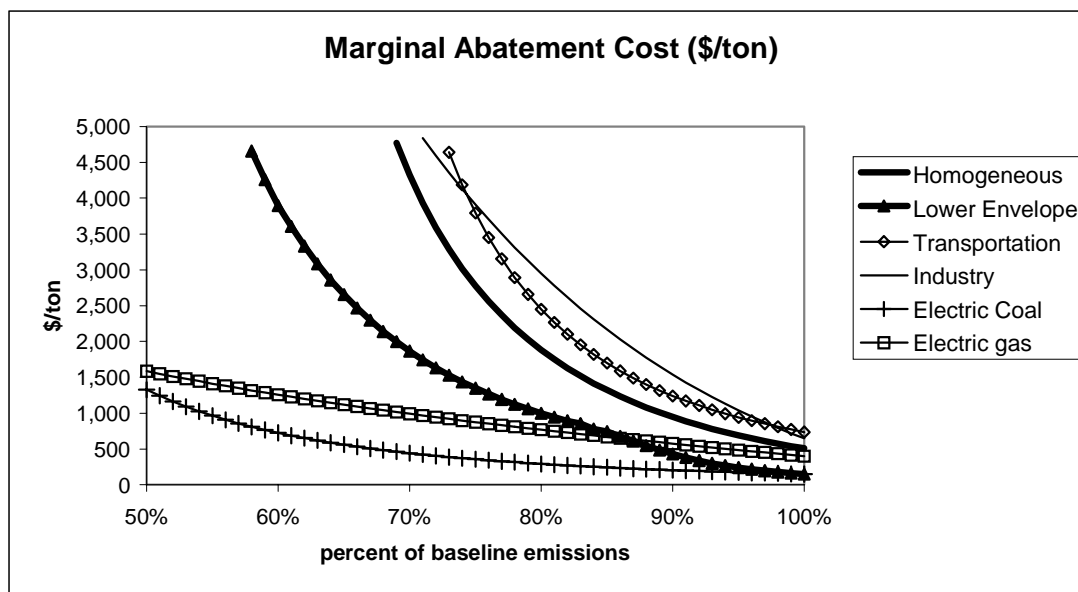


Figure 4: Partial equilibrium abatement cost functions used in the models.

The values of the abatement cost functions at the common benchmark and at a 25% reduction in emissions across all industries are reported in Table 1.¹⁴ The marginal abatement cost (MAC) for the Heterogeneous Case is not applicable (N/A) because different values are obtained in the constituent industries. The Homogeneous and Heterogeneous Cases have equal total costs. However, the cost of emission reductions is less for the Lower Envelope Case, which reflects cost-effective implementation that is assumed in its construction.

¹⁴ The 1990 Clean Air Act led to a roughly 21% reduction in NO_x across all sectors, according to Pechan (1996).

<i>Cases</i>	Benchmark			25% reduction		
	<i>MAC (1990\$ per ton)</i>	<i>Abatement Cost (million 1990\$)</i>	<i>Emissions* (million tons NO_x)</i>	<i>MAC (1990\$ per ton)</i>	<i>Abatement Cost (million 1990\$)</i>	<i>Emissions (million tons NO_x)</i>
Heterogeneous	N/A	3,703	17,444	N/A	9,018	13,082
Electricity: Coal	150	546	5,908	357	890	4,431
Electricity: Gas	400	29	591	875	122	443
Industry	650	144	3,418	3,912	1,838	2,563
Transportation	737	2,984	7,527	3,795	6,168	5,645
Homogeneous	510	3,703	17,444	2,778	9,018	13,082
Lower Envelope	150	3,703	17,444	1,348	6,439	13,082

* Unregulated emissions total 6,913 million tons, and are not included in this table.

Table 1: Characterization of NO_x abatement costs (\$1995)

4. Data

Calibration of the cost and expenditure functions used in the model requires data for benchmark cost shares, benchmark prices, and elasticities of substitution. In the following sections, data sources for the general economy and the abatement sector used to determine these parameters are described.

General Economy

Elasticity of substitution and cost share parameters for consumption and production are drawn from Goulder et al. (1999). Benchmark values for the pollution-intensive intermediate goods sectors are set to reflect the sector sizes in the 1990 economy. In order to isolate the impact of abatement technology heterogeneity within these sectors, the sectors are modeled with homogeneous productive sub-nest technologies. This is accomplished by benchmarking each of the four polluting intermediate goods sectors with the same input cost shares. The assumption of constant returns to scale implies that these sectors are scaled versions of each other with regard to the productive sub-nest. The elasticity of substitution between the productive and pollution abatement (BE) sub-nests in these sectors is set so that the role of abatement relative to other means of reducing emissions (input and output substitution) is no greater than that in the Goulder model.¹⁵ We explore alternatives in sensitivity analysis. The elasticities used in the model are listed in Table 2.

¹⁵ Emission reductions occur through three types of changes in production, referred to as “three channels” for abatement by Goulder et al. (1999). Technological abatement includes the out-of-pocket compliance costs incurred by industry, and is the usual measure included in partial equilibrium models. A second channel is input substitution, which results when the firm alters the relative intensity of factors of production. The third channel is output substitution, which results when the demand for production changes in response to changes in product prices. One of the main distinctions among the policies is the degree to

Utility: Upper nest	0.96
Utility: Consumption sub-nest	0.85
Final Goods (D, C)	0.8
Intermediate Dirty Goods $M=\{G_E, G_G, I, T\}$	
Upper nest	0.05*
Productive Aggregate	0.8
Abatement-Emissions Aggregate	
<i>Heterogeneous Case</i>	
G_E	0.89
G_G	2.2
I	1.8
T	0.62
<i>Homogeneous Case</i>	0.58-0.72
<i>Lower Envelope</i>	0.20-0.46
Intermediate Clean Good (N)	0.8
Intermediate Abatement Good (B)	1

* The value is 0 for the Technology Mandate.

Table 2: Elasticity of substitution parameter values.

Abatement Costs

Data for abatement costs come primarily from sources produced by the EPA, and are summarized in Table 1. Benchmark emission controls are those in place prior to the 1990 Clean Air Act Amendment, and we allocate emissions and control costs by industry. EPA (1998) provides emissions for electricity, industry, transportation, and other sources. The electricity emissions are allocated to coal and to gas and oil based on average emission rates and fuel use (Pechan 1996). Industry emissions are allocated to combustion sources and other processes, using information from both studies. Similarly, emission from transportation is divided between onroad and offroad sources; only onroad sources are included under transportation in the model.

The value of abatement in the benchmark is derived from EPA (1997). For stationary sources the annual capital and O&M (operating and maintenance) costs are included, and allocated by industry. EPA (1990) reports the costs of pollution control for transportation. For mobile sources,

which they employ these channels in achieving emission reductions. The least cost approach would employ all channels such that the marginal cost of reductions through each channel is equated.

In the Goulder model, for a 50% reduction under an emissions tax (with homogenous abatement costs), 79% of the reduction is achieved through the abatement effect, 18.5% through input-substitution, and 2.5% through output substitution. In our model, their approach is analogous to what we term the Lower Envelope Case. For a 50% reduction under an emissions tax in this case, we obtain 68% of the reduction through the abatement effect, 14% through input substitution, and 18% through output substitution.

the data accounts for reductions in O&M associated with improved vehicle performance stemming from emission related policies. However, the data does not associate costs with specific pollutants. White (1982) provides some evidence about the portion of cost for reducing volatile organic compounds and NO_x jointly that could be attributed to NO_x, but the allocation of costs in transportation to specific pollutants is necessarily arbitrary.

To estimate marginal abatement costs for a specific level of reduction for each industry, we solved for the substitution parameter in a CES production function that provided the best fit linking abatement expenditures and marginal cost in the benchmark with expected abatement expenditures and expected marginal (or average) abatement cost at a specified level of reductions. These values are reported in Table 2. Most of the scenarios for future reductions were obtained from Pechan (1996), but a number of other studies were consulted to estimate costs for future reductions from transportation. For the Homogeneous and Lower Envelope Cases, a single value of the substitution parameter would provide an appropriate representation of aggregation only for a specific level of reduction. Hence, the model was solved for a series of 1% reductions, and a substitution parameter identified for each step in this series, in order to provide an accurate aggregation over the range of reductions we consider. The ranges are reported in Table 2.

5. Characterization of policies

The benchmark describes emissions and costs associated with NO_x control preceding the 1990 Clean Air Act Amendments. We consider four alternative policy instruments for achieving further reductions.

Emission Tax

The emission tax is set endogenously to achieve a specified level of emission reduction below the benchmark levels. Within the model, this is achieved by endowing emissions to the government, which effectively sells emission rights to the polluting industries.¹⁶ Revenues are used by the government to reduce the tax on labor income, subject to the constraint that the absolute level of government spending remains constant.

Emission Permits

In modeling emission permits, the specified level of emissions are endowed to the representative household, which sells permits to industries. The income accruing to the household is analogous to changes in corporate earnings and shareholder wealth whereby assets accounted for at the industry level and, in turn, the change in earnings, accrues to the household as the owner of firms. Hence, no revenue is raised directly for the government, however the government does receive indirect revenue through the tax on corporate earnings.

¹⁶ The emissions tax would be equivalent to an emission permit approach were permits distributed by the government through a revenue-raising auction.

Performance Standard

Two policies have command and control characteristics in that emission reductions are imposed in a uniform manner across the four regulated polluting industries. The performance standard is modeled as an equal percentage reduction in allowable emissions by the four industries. Firms may achieve these reductions through technical abatement or through input substitution. In the model, emissions rights are endowed to the affected industries. Rents from the endowments of emissions (E) are offset directly with an output subsidy so prices are unaffected by the rents and budget neutrality is achieved. Emission reductions are implemented by reducing the endowments.

Technology mandate

The modeling of a technology mandate is similar to that for a performance standard. Equivalent percentage reductions are required of the regulated polluting industries, but there is no opportunity for input substitution to achieve the emission reductions. Specifically, managers are precluded from changing the intensity of the BE aggregate relative to other input factors to achieve requisite reductions. (However, input substitution within the productive sub-nest may still occur.)

Here, we assume the regulator has managed to mandate a technology that lies on the efficient schedule of options for each of the heterogeneous industries. This formulation could be interpreted as a favorable characterization of the regulatory process, analogous to the informed regulator in Goulder et al. (1999), because the regulator has solved the asymmetric information problem that is often associated with environmental regulation and has identified a specialized mandate for each industry. Were the regulator less than omniscient, analogous to the uninformed regulator in Goulder et al. (1999), the mandated technologies could lie off the cost-effective schedule for an industry. The one-size-fits-all criticism that one often hears of technology mandates is probably a characterization of the latter situation, and hence our model may be a generous portrayal of this instrument.

Evaluation of Policies

We evaluate the social costs of the policies, ignoring their environmental benefits. Two measurement issues affect the comparison. First, pollution abatement in the benchmark is not cost-effective because marginal abatement costs differ among the four regulated industries. The implementation of a cost-effective policy would lead to shifts in emissions among the industries, even in the absence of any change in the overall level of emissions from benchmark levels, resulting in a reduction in abatement costs but also resulting in emission increases in some industries. We assume that this type of emission “backsliding” is precluded, as has characterized the implementation of tradable permit programs in practice, so that no industry may increase emissions above benchmark levels. We examine the importance of this assumption in sensitivity analysis.

Second, even when backsliding is precluded and baseline emission levels are enforced, there exists an opportunity to reduce social costs through the substitution of an emission tax for an existing policy by recycling the tax revenue to reduce pre-existing taxes (Goulder 1999). Hence, we choose to normalize the costs of emission reductions by comparing the cost of each instrument relative to that of the most cost-effective instrument, the emission tax, at each level of

emissions. This approach ensures that all measures of the cost of emission reductions are of the same sign when we compare alternative policies.

We use equivalent variation to compare welfare under different policies. Equivalent variation measures the change in income at original prices that would lead to the same level of household utility as that achieved under a policy that led to lower emissions and new prices. Define $\mu(\mathbf{q}; \mathbf{p}, m)$ to be the income that the household would require at new prices \mathbf{q} to be as well off as it was at original prices \mathbf{p} with income m .¹⁷ Denote the *benchmark* by superscript “B.” Denote an alternative policy as the *current policy* (sometimes abbreviated to “cp”) that describes the current level of emissions and the policy that is modeled. Then the equivalent variation measure is:

$$EV^{cp,B} = \mu(\mathbf{p}^B; \mathbf{p}^{cp}, m^{cp}) - \mu(\mathbf{p}^B; \mathbf{p}^B, m^B) = \mu(\mathbf{p}^B; \mathbf{p}^{cp}, m^{cp}) - m^B$$

We denote the solution to the model when a tax is used to achieve a level of emissions equivalent to those in the benchmark as the *baseline tax* (sometimes abbreviated to “bt”). The relative welfare cost for achieving emission reductions using various policies compared to baseline tax is the difference in magnitude of equivalent variation:

$$\begin{aligned} EV^{cp,B} - EV^{bt,B} &= \mu(\mathbf{p}^B; \mathbf{p}^{cp}, m^{cp}) - \mu(\mathbf{p}^B; \mathbf{p}^{bt}, m^{bt}) \\ &= \text{welfare}_{\text{current policy}} - \text{welfare}_{\text{baseline tax}} \end{aligned}$$

For convenience, in evaluating policies we normalize so that the welfare cost of achieving emission reductions for any policy is expressed relative to the cost using an emissions tax. Hence, the welfare measure we employ is the following ratio:¹⁸

$$\frac{(\text{welfare}_{\text{current policy}} - \text{welfare}_{\text{baseline tax}})}{(\text{welfare}_{\text{current tax}} - \text{welfare}_{\text{baseline tax}})}$$

6. Findings

Our interest is in the relative cost-effectiveness of the policy instruments, and how the relative cost varies in each of the three representations of abatement cost: the Heterogeneous Case, the Homogeneous (aggregate) Case, and the Lower Envelope (aggregate) Case.

¹⁷ Varian, 1992.

¹⁸ The previous literature has used a similar expression, except that the denominator involves the welfare cost of an emissions tax in the first best case, absent pre-existing labor taxes:

$$\frac{\text{welfare}_{\text{current policy}} - \text{welfare}_{\text{baseline policy}}}{\text{welfare}_{\text{current (First Best) tax}} - \text{welfare}_{\text{baseline (First Best) tax}}}$$

The disadvantage of this approach is that in a first best world, there would be increases in economic activity and an increase in emissions and/or labor, compared to what is observed in the benchmark (Goulder et al. 1997; Goulder et al. 1999).

Throughout the analysis we find that the least expensive instrument is the emission tax. Second and third, for *initial* reductions, are the two variations of command and control regulation, the performance standard and the technology mandate, always in this order. These two policies differ only in that the performance standard allows for input substitution as a means of meeting the emission limit, while the technology mandate is constrained away from this, and consequently incurs greater abatement cost to achieve the same level of reductions. The most expensive policy for initial reductions is tradable permits, because it generates rents associated with the asset value of permits that exacerbate pre-existing distortions resulting from the labor tax. These rents accrue to households rather than to the government as in the case of the emission tax, and hence are not available to reduce the pre-existing tax. The rents accrue over all emissions, while abatement costs accrue only over reductions. For an incremental initial reduction, the permit rents swamp other components of cost, making permits more expensive than the command and control policies.

Figure 5 illustrates the relative cost of instruments for the Heterogeneous Case over a range of emission reductions from 0-50% of benchmark levels. The cost of each instrument is expressed as a ratio of the welfare cost for emission reductions using a given policy to that using an emission tax. Two points of interest are illustrated in the figure. First, the dominance of command and control policies over tradable permits at initial emission reductions is quickly overturned. At a 4% level of emission reduction, permits emerge as less costly than the other non-revenue-raising instruments, where they are about 4.5 times as expensive as an emission tax. The dominance of a permit policy over the command and control approaches is maintained over the remaining emission reductions that are modeled. At a 25% reduction in emissions, permits are about 1.6 times as expensive as an emission tax, while a performance standard is 2 times and a technology mandate is 2.2 times more expensive.

Second, the curves exhibit a subtle wiggle that stems from the anti-backsliding constraint. The constraint affects only the tax and permit policies because they provide an incentive for equalization of marginal costs among industries, which would lead to an increase in emissions in some industries absent the constraint. The constraint is relaxed when the marginal abatement cost among industries with positive abatement rises above the cost for a given industry that still has benchmark level emissions, so it too begins to reduce emissions. The contribution of positive emission reductions from an additional industry lowers the rate of change in the marginal cost of further “percent reductions,” producing a wiggle. Although only permits and taxes are affected by the constraint, all the curves are affected because taxes appear in the denominator of each ratio.

We now turn to a comparison of the Heterogeneous Case with the Homogeneous Case. Figure 6 illustrates the relative cost of instruments in the Homogeneous Case when abatement costs are aggregated for the economy. By construction, the aggregation has no effect on the partial equilibrium marginal abatement cost for the command and control policies. However, it does have an effect on the representation of the more flexible policies because it fails to reflect cost-effective emission reductions that these policies may realize. Again however, all policies in the figure are affected because taxes appear in the denominator of each ratio. Hence, there is a downward shift in the command and control curves in Figure 6, compared with Figure 5.

The costs for tradable permits and for the emissions tax are both increased relative to the heterogeneous representation of abatement, but they are increased by proportionately more for tradable permits. Hence, the dominance of command and control policies over tradable permits

that is evident for initial emission reductions in this case survives beyond a 25% reduction. The welfare cost of tradable permits relative to taxes is about 1.5 for a 25% reduction in emissions, where a performance standard is about 1.2 times more expensive, and a technology standard is 1.4 times more expensive than a tax. Performance standards dominate permits until a 39% reduction is achieved, at a cost of about 1.35 times more than a tax.

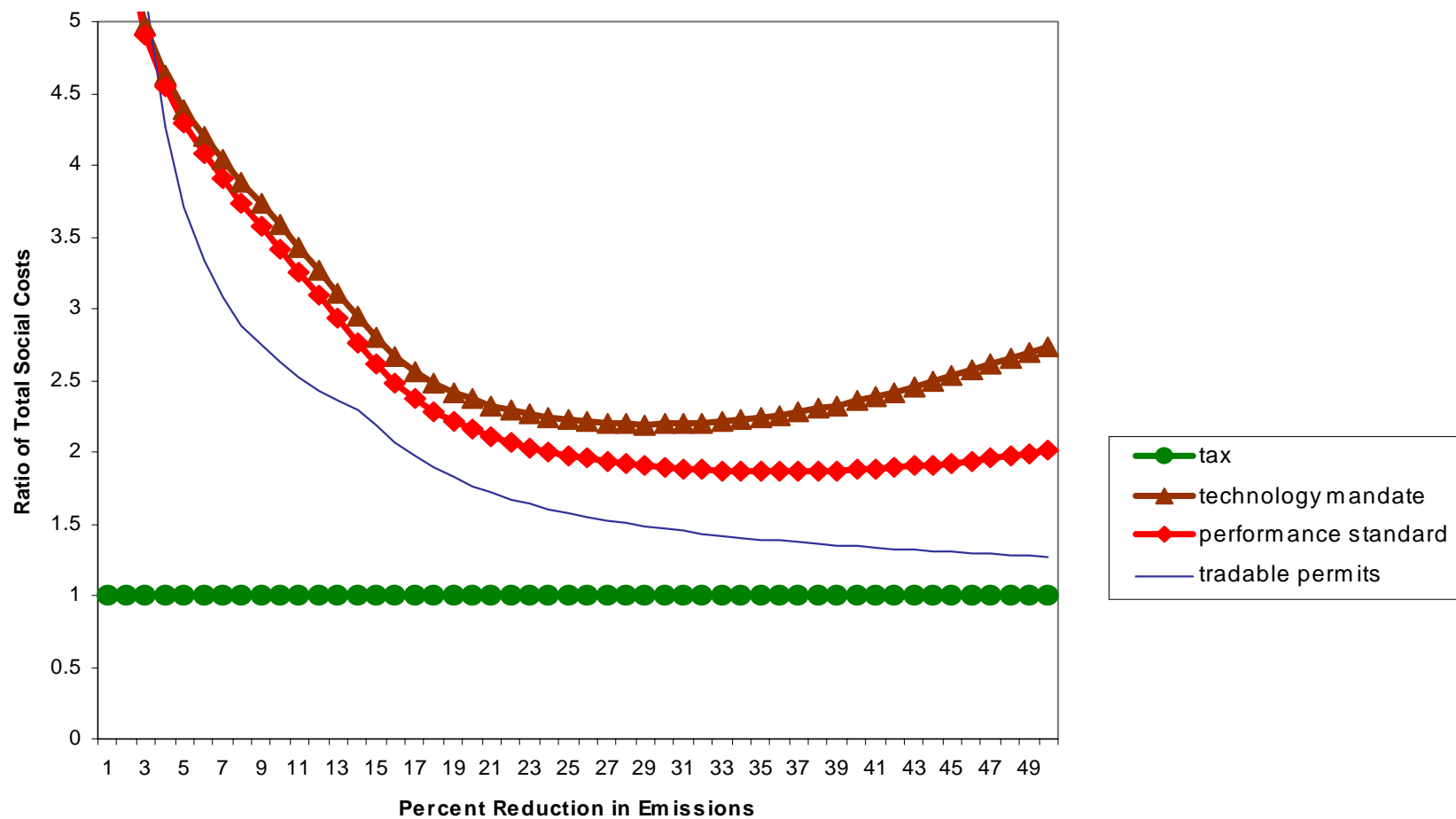


Figure 5: Ratio of total social cost of various policies to total social cost of tax in the Heterogeneous Case.

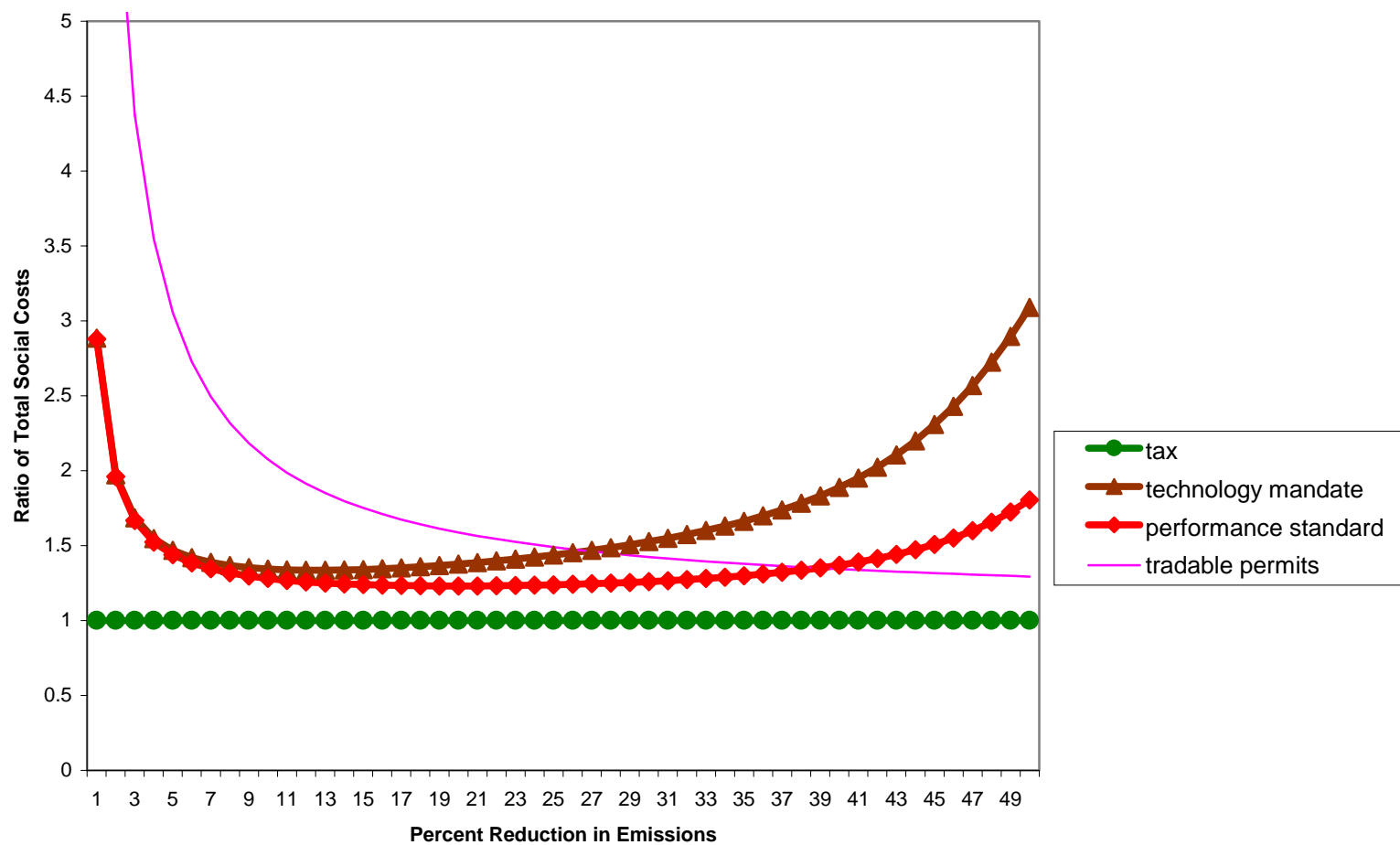


Figure 6: Ratio of total social cost of various policies to total social cost of tax in the Homogeneous Case.

The measures of total social cost (welfare cost), marginal social cost, and marginal (technical) abatement cost for a 25% reduction for all cases are reported in Table 3. The welfare cost under a tax increases from the Heterogeneous Case to the Homogeneous Case by \$1,434 million. The welfare cost under tradable permits increases by even more, \$1,968. However, there is only a slight increase in the welfare costs of a performance standard and technology mandate in moving from a Heterogeneous to a Homogeneous Case.¹⁹ Hence, these differences point toward quite different policy prescriptions, depending on the modeling approach. In the Heterogeneous Case, tradable permits appear much less expensive than a performance standard or technology standard. However, in the Homogeneous Case, permits are more expensive.

	Technology Mandate	Performance Standard	Tradable Permits	Tax
<i>Total Social Cost</i>				
<i>(\$Millions)</i>				
Heterogeneous	4,603	4,092	3,254	2,070
Homogeneous	5,035	4,339	5,222	3,504
Lower Envelope	2,481	1,722	2,419	1,476
<i>Marginal Social Cost</i>				
<i>(\$/ton)</i>				
Heterogeneous	1,860	1,538	1,128	921
Homogeneous	2,125	1,649	1,618	1,292
Lower Envelope	1,088	657	740	551
<i>Marginal Abatement Cost</i>				
<i>(\$/ton)</i>				
Heterogeneous	1,830	1,212	604	605
Homogeneous	2,110	1,263	743	745
Lower Envelope	1,084	465	324	325

Table 3: Cost measures for 25% reduction in emissions (\$1995).

¹⁹ The reported marginal abatement costs for the Heterogeneous and Homogeneous Cases differ in Table 3 due to the difference in the way production is modeled. This is discussed further in sensitivity analysis.

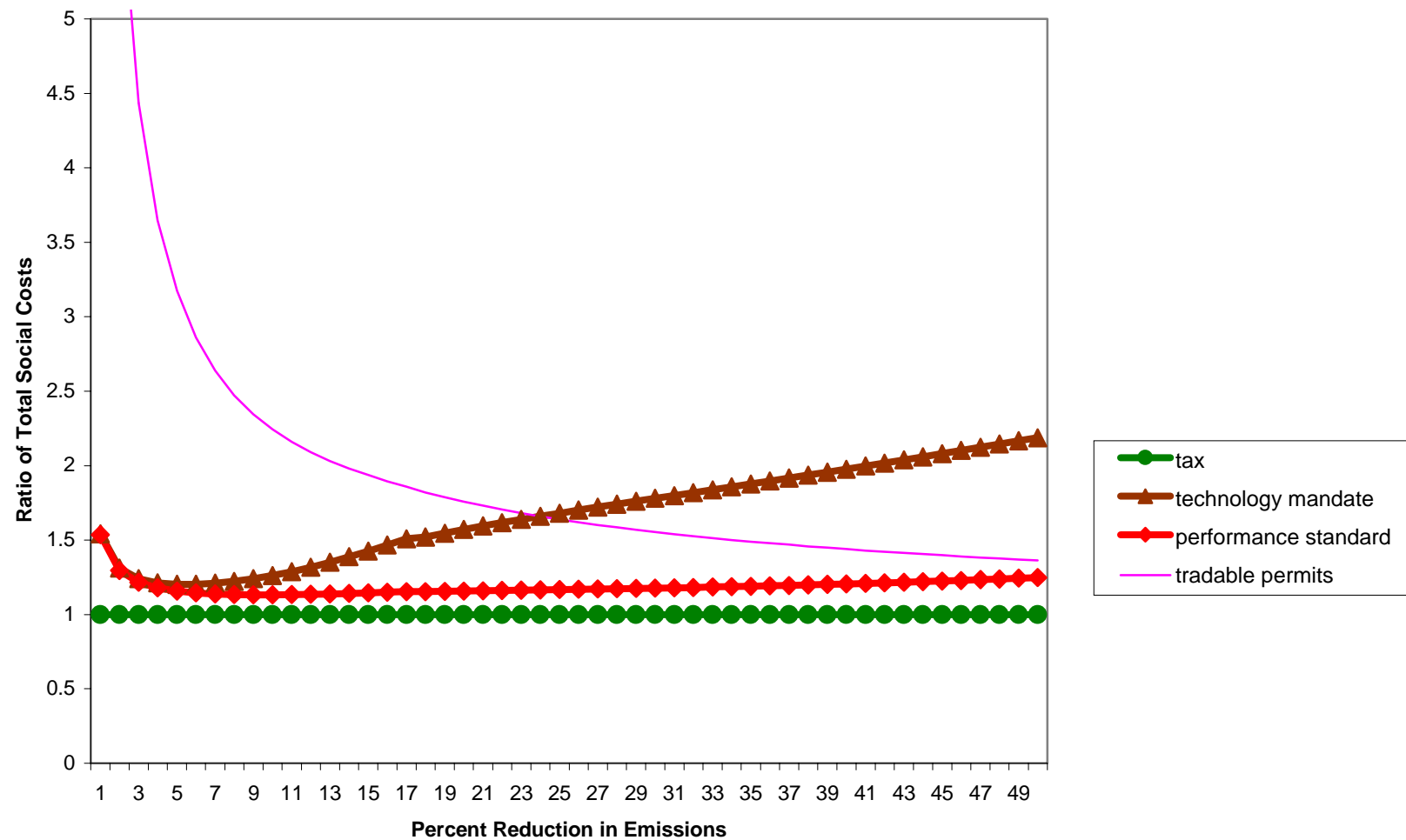


Figure 7: Ratio of total social cost of various policies to the tax in the Lower Envelope (cost-effective) Case.

We also investigate the alternative aggregation method embodied in the Lower Envelope Case in Figure 4, in which the abatement cost curve is constructed around a cost-effective schedule for abatement. The comparison of instruments is illustrated in Figure 7 and in Table 3. In this case a technology mandate would dominate tradable permits up to about a 24% reduction in emissions, in which the costs of these instruments are about 1.7 times that of an emissions tax.²⁰ A performance standard would dominate tradable permits throughout the modeled range of reductions. This is a dramatic reversal in policy prescription compared to the Heterogeneous Case, in which tradable permits dominate over almost the entire modeled range of reductions.

	Technology Mandate	Performance Standard
<i>Heterogeneous</i>	4	4
<i>Homogeneous</i>	27	39
<i>Lower Envelope</i>	24	>50

Table 4: Percentage of emission reduction when the social cost for tradable permits becomes less than that for command and control policies.

The actual point at which tradable permits begin to dominate other policies in the alternative specifications of abatement cost is reported in Table 4. Recall that taxes always have the least social cost; performance standards always dominate a technology mandate; and tradable permits always have the greatest cost for initial emission reductions. Table 4 indicates that tradable permits begin to dominate both command and control policies at a 4% reduction in emissions in the Heterogeneous Case. In the other cases, permits do not dominate a technology mandate until about 25% reduction in emissions is achieved. The number is much greater still when comparing permits with a performance standard.

In a partial equilibrium model, emission reductions are achieved through technological abatement. In a general equilibrium model, there are three potential channels for emission reduction: (1) output substitution, or a reduction in demand resulting from increases in product prices; (2) input substitution, or the greater use of inputs with lower intensity of emissions; and (3) technological abatement. An indication of how the emission reductions are achieved is evident in Table 5, which reports the percentage of emission reductions that result from each channel. Note that the technology mandate precludes input substitution as a means of achieving necessary reductions. Output substitution is relevant for both a technology mandate and performance standard, but it is much less potent than for the incentive-based policies. The reason is that permits and taxes incorporate the

²⁰ These results are qualitatively similar to those reported in Goulder et al. (1999). For emission reductions of 25%, using a different formulation to express relative costs (see footnote 15) they find the cost of the permit policy is more than double that of the tax.

opportunity cost of emissions into product prices, through the price of permits or the tax revenues that must be paid, and hence they have a larger effect on output.

(percent)	Technology Mandate	Performance Standard	Tradable Permits	Tax
<i>Heterogeneous</i>				
Output	5	5	21	20
Input	0	14	10	10
Abatement	95	81	69	70
<i>Homogeneous</i>				
Output	6	5	29	29
Input	0	18	13	13
Abatement	94	77	58	59
<i>Lower Envelope</i>				
Output	3	2	16	15
Input	0	21	16	17
Abatement	97	77	68	68

**Table 5: Percent reduction through alternative channels
for a 25% emission reduction.**

In moving from the Heterogeneous Case to the Homogeneous Case, the contribution of technological abatement in achieving emission reductions is decreased. This is especially true for the incentive-based policies in which the role of technical abatement is around 70% for permits and taxes in the Heterogeneous Case, but it falls to around 60% in the Homogeneous Case. Incentive-based policies are most able to capture cost savings associated with heterogeneity in technological abatement, but this is precluded in the aggregation to the Homogeneous Case. Hence, output and input substitution have to play a greater role in the Homogeneous Case, which contributes to the greater estimation of costs. However, the Lower Envelope Case is quite similar to the Heterogeneous Case for permits and taxes, because both yield cost-effective technological abatement.

7. Sensitivity Analysis

In order to examine the robustness of the results described above, sensitivity analysis was performed on several model parameters and on the model structure. One important parameter is the upper nest elasticity of substitution between the productive and pollution abatement subnests for the production of intermediate goods (see Figure 2). An increase in this parameter would increase the ability to trade off between abatement and input substitution. As a result, we would expect the distinction in the way technological abatement is modeled in the Heterogeneous and Homogeneous Cases to be less significant, especially for tradable permits. In addition, we expect the distinction between a

technology mandate and a performance standard to be greater in all the cases, because the technology mandate is modeled as having an upper nest elasticity of substitution of zero.

To explore this issue, we replicate our experiment with alternative values for the upper nest elasticity of substitution. In Table 6 we report the total social costs for a 25% reduction in emissions for the central value of 0.05 as well as for alternative values of 0.02 and 0.08. The difference in total social costs for tradable permits falls by 6% when comparing the Heterogeneous and Homogeneous Cases using an elasticity of 0.08, implying a greater opportunity for input substitution and a less important role for heterogeneity in abatement costs, as anticipated. Conversely, the difference between the models is greater when a lower elasticity value is used.

Furthermore, the difference between technology mandates and performance standards in all models is greater when the elasticity is greater. The cost of the technology mandate is invariant, while the cost for performance standards responds to the opportunity for input substitution as a way of lowering the cost of emission reductions.

Another important parameter in the model is the magnitude of the pre-existing tax rate on labor income. Were the tax rate greater, we expect the distinction between the Heterogeneous and Homogeneous models to be greater with respect to the relative performance of permits and taxes, because of the inability of grandfathered permits to provide revenue that can lower the labor tax. The value in the central case is 0.4. We explore alternatives of 0.3 and 0.5 and the results are reported in Table 6. Only tradable permits are significantly affected when viewing the absolute value of total social costs, and the change is in the predicted direction.²¹ A lower pre-existing tax makes tradable permits less expensive, and a greater tax increases their cost.

²¹ Benchmark social welfare is changed under alternative values for the labor tax, which yields slight changes in the cost of all the policies.

	Technology Mandate	Performance Standard	Tradable Permits	Tax
<i>Central case*</i>				
Heterogeneous	4,603	4,092	3,254	2,070
Homogeneous	5,035	4,339	5,222	3,504
Lower Envelope	2,481	1,722	2,419	1,476
<i>Sigma top = .02</i>				
Heterogeneous	4,603	4,370	3,382	2,144
Homogeneous	5,033	4,701	5,518	3,651
Lower Envelope	2,481	2,042	2,764	1,626
<i>Sigma top = .08</i>				
Heterogeneous	4,603	3,875	3,142	2,004
Homogeneous	5,037	4,076	4,983	3,383
Lower Envelope	2,481	1,540	2,183	1,369
<i>Labor tax = .3</i>				
Heterogeneous	4,609	4,098	2,959	2,073
Homogeneous	5,042	4,345	4,793	3,509
Lower Envelope	2,484	1,724	2,185	1,479
<i>Labor tax = .5</i>				
Heterogeneous	4,596	4,086	3,548	2,067
Homogeneous	5,028	4,332	5,650	3,499
Lower Envelope	2,478	1,720	2,652	1,474

*In the central case the parameters are: sigma top = .05, labor tax = .4

Table 6: Total social cost (million \$1995) for a 25% reduction in emissions.

The feature of “no backsliding” is imposed in the central model to acknowledge the practical constraint that emissions cannot increase in any one sector with the adoption of flexible, cost-effective instruments such as permits or taxes. We explore the importance of this constraint by allowing backsliding. For a 25% reduction in emissions, the no backsliding constraint is not binding in any of the four intermediate goods sectors. The constraint does have an effect, however, for smaller levels of reductions. When backsliding is allowed, total social welfare increases with the introduction of taxes in place of benchmark regulation. Indeed, this regulatory reform allows for emissions to be reduced by up to 8% before total social costs rise above those that obtain in the benchmark.

A more abstract feature has to do with the general equilibrium representation of the structure of production. By construction, the aggregation to the Homogeneous Case has no effect on the partial equilibrium marginal abatement cost schedule for the command and control policies. Similarly, aggregation to the Lower Envelope Case has no effect on the partial equilibrium marginal abatement cost schedule for the cost-effective policies. However, in Table 3 the reported general equilibrium

marginal abatement costs differ in each case. The reason is that in the aggregate cases the relative intensity of the productive and pollution abatement subnets for intermediate goods are set to be equal for all sectors, while they differ in the Heterogeneous Case. An alternative would be to preserve the structure from the disaggregate model and implement the Homogeneous or Lower Envelope Cases by imposing constraints on emissions. Under all policies, this would require an equal percent (cost-ineffective) reduction in all sectors in the Homogeneous Case, while requiring a cost-effective allocation of reductions in the Lower Envelope Case.

We explore this formulation in detail and find that quantitative results differ slightly from those reported in Table 3. The (social) marginal abatement costs for the command and control policies become identical in the Heterogeneous and Homogeneous Cases. Similarly, this approach yields identical (social) marginal abatement costs when comparing the Heterogeneous and Lower Envelope Cases under tradable permits and the tax. This might be a meaningful way to represent regulatory behavior that failed to account for heterogeneity. However, the disadvantage of this approach is that it does not reflect well the failure of an economic model to represent heterogeneity. This alternative incorporates detailed sector-specific information about production and abatement, and then effectively turns it off when solving the model by imposing constraints on how emission reductions are achieved. For this reason we choose not to adopt this as our central case. Nonetheless, we find the main results of the paper are unaffected by this choice of model specification.

Finally, in our central model, goods are imperfect substitutes in the production of other goods or in final consumption. As an alternative, we construct a model with two polluting industries that produce perfect substitutes, but have different abatement cost schedules. To model production such that both industries remain in operation after the introduction of a policy that reduces emissions, we introduce two new factors of production that could be thought of as resources (R_1 and R_2) used in different proportions by the two firms in the benchmark. In the limiting case, as the ratio of the use of these factors by a firm approaches infinity or zero, this formulation converges to the case of a fixed factor in production. As the ratio approaches 50:50, the industries become identical, and one industry shuts down when emission reductions impart a cost advantage to the other industry. For ratios in the benchmark different than 50:50, both industries remained in business and meaningful results were obtained. Using this alternative modeling structure we are able to replicate the main results of the paper. The sensitivity to the ordering of instruments appears robust in these various scenarios, suggesting the importance of modeling a regulated sector with a sufficient level of detail to capture inherent cost heterogeneity.

8. Conclusion

Two primary insights have emerged from the burgeoning literature on the cost-effectiveness of alternative environmental policies considered in a second-best setting. One is the absolute importance of pre-existing distortions away from economic efficiency, particularly pre-existing factor taxes, in determining the full social cost of regulation. A significant cost advantage accrues to policies that raise revenues that can be used to reduce pre-existing distortionary taxes. A second insight is that the relative performance of tradable permits is so penalized when permits are freely allocated (and therefore raise no revenue) that they can be dominated by command and control approaches.

This paper reaffirms the first of these insights, but casts doubt on the generality of the second. We find that when heterogeneity of abatement costs is accounted for in a fairly simple way, the relative performance of tradable permits improves significantly, and this instrument out-performs command and control approaches over a wide range of emission reductions. Two aspects of tradable permits seem relevant. One is the advantage this policy has with respect to heterogeneity in abatement cost, because it tends to achieve equality in marginal abatement costs. The other is the disadvantage that stems from interaction with pre-existing taxes. We find the former aspect dominates over all except the initial range (less than 4%) of emission reductions. The reason is that heterogeneity in abatement costs lowers the relative cost of technological abatement for tradable permits (and taxes) compared to command and control approaches. This in turn lowers other social costs fueled by its interaction with pre-existing taxes.

Our findings provide a justification for greater detail in economic modeling. However, more detail comes at greater cost. We suggest investigators can be reasonably confident that this issue is not undermining model results if technological abatement cost functions estimated outside of a general equilibrium model, in a detailed sector model, vary little for each type of instrument being considered. If differences in cost are significant (for example, because heterogeneity is significant), then this should be accounted for in the general equilibrium framework. It may be adequate to apply different aggregate abatement cost functions when considering different instruments, as illustrated by the Homogeneous and Lower Envelope Cases, but this runs the risk of covering up subsidiary issues.

This paper considers the cost of NO_x reductions in the United States, and the generality of these findings with respect to other pollutants is uncertain. However, the heterogeneity in the cost of NO_x reductions is not unusual in comparison to other pollutants. For example, Carlson et al. (2000) examined the marginal cost of sulfur dioxide control within the U.S. electricity sector and found the standard deviation is three times the mean for 678 power plants. In cases where abatement has little or no role, such as in reducing carbon dioxide emissions, the issue of heterogeneity in abatement is, of course, irrelevant. Heterogeneity in other features of the model, for example in the ability to use input substitution to reduce emissions, may be of importance.

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Appendix

Utility for representative household	U
Factors	
Final goods	
Direct consumption of natural gas	G
Other emission-intensive consumption goods	O
Clean consumption good	C
Intermediate goods	
Coal-fired electricity production	C_E
Gas-fired electricity production	G_E
Industrial combustion	I
Transportation	T
Clean intermediate goods	N
Abatement	B
Primary factors	
Labor	L
Emissions	E
Parameters	
Share parameters	θ
Substitution parameters	ρ
Elasticity of substitution	σ^*
Time endowment	H
Revenue transfer from government	TR
Variables	
Labor tax	t_L
Prices	p

* Note $\rho = \frac{(\sigma - 1)}{\sigma}$, where σ is the elasticity of substitution.

Table A1: Notation.